



RESEARCH ARTICLE

Mitigating water scarcity in arid sandy soil using a biodegradable superabsorbent polymer: Effects on productivity, soil health and nutrient dynamics in cluster bean (*Cyamopsis tetragonoloba* (L.) Taub.)

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Abstract

A field experiment was carried out to study the effect of EF Polymer (Fasal Amrit) on the germination, growth, yield and water requirement of cluster bean (*Cyamopsis tetragonoloba* (L.) Taub.) in sandy soil during the kharif seasons of 2023 and 2024. The experiment was conducted at BAIF's Desert Research Centre, Undkha, Rajasthan, under the technical guidance of the Central Research Station (CRS), Uruli Kanchan, Pune. The experiment comprised 10 treatments evaluating three application rates of Fasal Amrit (15, 20 and 25 kg ha⁻¹) in combination with 100, 85 and 75 % of the recommended dose of fertilisers (RDF), along with a control treatment receiving 100 % RDF without polymer application. Application of Fasal Amrit at 20 kg ha⁻¹ combined with 85 % of the RDF resulted in the highest fresh pod yield across both cropping seasons, outperforming all other treatments. Treatments receiving Fasal Amrit at 20 and 25 kg ha⁻¹ in combination with 100 % RDF ranked next in yield performance. Application of Fasal Amrit at 20 kg ha⁻¹ combined with 85 % RDF reduced the number of irrigations from nine (control) to six and extended the irrigation interval up to 14 days, demonstrating enhanced soil moisture retention and improved water-use efficiency across both years.

Keywords: economic analysis; growth parameters; guar; hydrogel-based soil amendments; soil properties; water-use efficiency

Introduction

The global population is increasing rapidly, while global water resources are steadily declining, particularly in regions where light-textured soils dominate agricultural production (1, 2). Agriculture alone consumes nearly 85 % of available water resources, compared to 15 % for industrial use and 5 % for domestic use. Consequently, water conservation has become a critical priority, as water scarcity severely affects the productivity of crops. There is a requirement for effective water sources for decreasing water losses (3, 4).

Irrigated agriculture remains the predominant consumer of freshwater worldwide and increasing water scarcity poses a serious challenge particularly in arid and semi-arid cropping systems. Rising temperatures and irregular rainfall patterns are expected to intensify drought frequency and severity. Under drought conditions, reduced plant water status lowers cellular turgor and leaf water potential, restricts photosynthesis and impairs metabolic processes, ultimately leading to significant yield losses (5). Therefore, developing effective water-management strategies is essential to sustain crop productivity and improve water-use

efficiency in water-limited environments. Soils in arid and semi-arid regions are typically characterised by low organic matter content, limited clay fraction, low annual rainfall and poor water-holding capacity (5–7). Improving the physical and hydraulic properties of these soils is therefore critical for enhancing water-use efficiency (WUE), increasing crop productivity and supporting global food security (5, 8). As water availability remains one of the primary constraints to agricultural production (9), effective strategies to retain rainfall and irrigation water within the root zone for extended periods are particularly important in water-limited environments (6, 7). Among effective strategies are advanced approaches that help maintain soil moisture and optimise irrigation intervals (10). Adjusting irrigation scheduling through direct evaporation measurements using evaporation pans allows precise estimation of the timing and quantity of water required by the crop. Providing the suitable amount of water at right time minimises adverse effects of drought stress (1). Another promising approach is the efficient utilisation and conservation of water resources through the application of superabsorbent polymers, which enhance soil moisture retention.

Superabsorbent polymers (SAPs) are cross-linked hydrophilic polymers capable of absorbing and retaining large quantities of water relative to their own mass and have been widely reported to improve soil moisture retention and plant water availability under drought conditions (11–13). When incorporated into soil, SAPs enhance water-holding capacity by absorbing irrigation or rainfall water and gradually releasing it to plant roots, thereby improving soil moisture availability under water-limited conditions (14). Their application has also been reported to improve soil aggregation, structural stability, aeration and rhizosphere functioning, contributing to enhanced root growth and reduced drought stress (15–17). However, maximising productivity under drought conditions requires the integration of SAP application with the cultivation of inherently drought-tolerant crop varieties. Cluster bean (*Cyamopsis tetragonoloba* L.), commonly known as guar, is an annual deep-rooted, heat-tolerant legume adapted to arid and semi-arid regions and capable of maintaining productivity under moisture-limited conditions (18, 19). Although it is generally drought-resistant, the crop becomes vulnerable to moisture stress during its flowering and pod formation stages (20). Because cluster beans have good nutritional value and play an important role in dryland farming and since earlier research has shown that soil conditioners can lessen the harmful impacts of drought on many crops, this study aims to evaluate the yield, yield components and soil health of guar under water-deficit conditions. Specifically, it investigates the impact of coating guar seeds with superabsorbent polymers on their morphological traits, physiological responses and overall productivity in field conditions. Using superabsorbent seed treatments may offer an environmentally friendly, economical and sustainable approach to improving cluster bean performance in drought-prone areas.

Materials and Methods

Experimental site, climate and soil characteristics

A field experiment was conducted during the kharif seasons of 2023 and 2024 at BAIF's Desert Research Centre, Undkha, Barmer, Rajasthan, to evaluate the impact of EF Polymer (Fasal Amrit) on cluster bean grown under sandy soil conditions. The experimental site is located in the hot arid zone of western Rajasthan (Thar Desert region) and is characterised by sandy soils, extremely high summer temperatures, low and erratic rainfall and high evaporative demand. The site lies between 24.4–26.5° N latitude and 72.1–73.9° E longitude, at an elevation of approximately 113 m above mean sea level.

The soil of the experimental field was sandy in texture with medium to high nutrient content. Initial soil characteristics showed a pH of 7.62, electrical conductivity (EC) of 0.39 dSm⁻¹, organic carbon (0.36 %) and available N, P and K levels of 120, 19 and 160 kg ha⁻¹ respectively. The climate during the crop-growing period exhibited considerable variation in maximum and minimum temperatures, ranging from 31.0–43.5 and 27.3–37.1 °C respectively. Morning humidity fluctuated between 10 and 81 %, while evening humidity ranged from 65–91 %. Only a few weeks of recorded rainfall, confirming the moisture-stressed environment. These climatic and soil conditions make the site ideal for evaluating moisture-retention products like Fasal Amrit.

Experimental details

The experiment was planned out with a randomized block design (RBD) comprising 10 treatments replicated three times. The

treatments consisted of combinations of 3 Fasal Amrit levels (15, 20 and 25 kg ha⁻¹) and three fertiliser levels (100, 85 and 75 % of recommended dose of fertilisers (RDF)) along with a control receiving 100 % RDF alone. The RDF for cluster bean was 10:40:0 kg ha⁻¹ (N:P:K).

Fasal Amrit was incorporated into the soil before sowing according to the respective treatment levels, along with the RDF. The experiment used the cluster bean variety 'Swati 444+'. The crop was sown in July 2023 and August 2024 respectively. The variation in sowing dates between years was due to differences in the onset and distribution of monsoon rainfall and sowing was undertaken following adequate soil moisture availability to ensure uniform crop establishment, by dibbling seeds at 30 × 10 cm spacing and size of each plot was 4 × 3 m (gross) and 3.8 × 2.4 m (net) during both years. Soil moisture was monitored in each treatment plot before irrigation using a soil moisture indicator. Irrigation was scheduled treatment-wise based on soil moisture depletion and water was applied when soil moisture reached the predefined stress threshold to avoid severe crop stress. The number of irrigation and irrigation intervals were recorded for each treatment throughout the crop growth period.

Soil sampling procedure and analytical methods

Soil samples were collected from the 0–15 cm depth before sowing and after harvest of cluster bean during both experimental years to assess treatment effects on soil properties. For each treatment plot, five sub-samples were randomly collected and composited to obtain one representative sample, whereas an initial composite soil sample was collected from the entire experimental field to determine baseline characteristics. Soil samples were air-dried, ground and passed through a 2 mm sieve prior to analysis following standard-soil analytical procedures (21). Soil pH and EC were determined in a 1:2.5 soil-water suspension using standard procedures. Organic carbon was estimated by the Walkley and Black method, available nitrogen by the alkaline KMnO₄ method, available phosphorus by the Olsen method and available potassium by flame photometry. Micronutrients (Cu, Fe, Zn and Mn) were extracted using DTPA and quantified using an atomic absorption spectrophotometer. All analyses were carried out at BAIF's Soil Testing Laboratory, CRS, Uruli Kanchan, following standard soil analysis protocols.

Statistical analysis

The recorded data on growth parameters, yield attributes, fresh pod yield, dry biomass yield, nutrient uptake, soil properties and irrigation behaviour were subjected to analysis of variance (ANOVA) appropriate for a RBD using OPSTAT statistical software. The significance of treatment effects was tested at the 5 % probability level ($p \leq 0.05$). Standard error of mean (SEm) and critical difference (CD at 5 %) were calculated for comparing treatment means. Data from both years were tested for homogeneity of error variance and, as the variances were homogeneous, the data were pooled for combined analysis to assess overall treatment effects.

Results and Discussion

Effect of Fasal Amrit and recommended dose of fertilisers on growth parameters

Plant height

Pooled data of both years for application of Fasal Amrit in combination with recommended fertiliser levels significantly

influenced plant height at both the first and last pickings (Table 1 and Fig. 1). The maximum plant height (38.47 cm) was recorded in treatment T_2 (Fasal Amrit at 20 kg ha⁻¹ + 100 % RDF) at the first picking (Fig. 2). Treatments $T_6 > T_5 > T_3 > T_1$ were statistically at par with T_2 , indicating that moderate to higher doses of Fasal Amrit coupled with optimal or slightly reduced RDF were equally effective.

At the last picking, the maximum height of 44.00 cm was observed under T_3 (Fasal Amrit at 25 kg ha⁻¹ + 100 % RDF), followed statistically by T_2 (42.53 cm) and T_6 (40.69 cm). The increase in plant height with higher Fasal Amrit doses may be attributed to improved soil moisture retention, nutrient availability and rhizosphere health, which together enhance vegetative growth. Previous studies have revealed that hydrophilic polymers enhance soil water-holding capacity and nutrient-use efficiency, leading to enhanced crop growth under varied moisture regimes (15, 18).

Number of branches per plant and number of root nodules at flowering

The pooled data of both years showed number of branches per plant ranged from 13.90–16.71 under the different treatment combinations (Table 1). The maximum value of the number of branches (16.71) was recorded in the treatment T_6 , followed by T_7 (15.97) and T_8 (15.84), while the minimum number of branches (13.90) was observed under T_{10} . Although numerical variations existed among the treatments, the variation was statistically non-significant, indicating that application of Fasal Amrit along with varying fertiliser doses did not exert a strong influence on branching behaviour.

The branching of legume crops is generally influenced by varietal characteristics and environmental factors such as light,

temperature and nutrient balance rather than soil conditioners alone. The non-significant effect seen in this study corresponds with earlier findings where superabsorbent polymers did not markedly alter branching patterns but improved moisture availability (22) and hydrogels primarily influence vegetative vigour through moisture retention rather than altering shoot vegetative structure such as branching (23, 24).

The pooled value of the number of nodules per plant ranged from 2.54–3.63, with highest nodule count recorded in T_6 (3.63), followed by T_7 (3.50) and T_1 (3.34), while the minimum value of nodules per plant (2.54) was observed under T_{10} . Similar to branching, nodule formation also did not show significant variation among treatments.

However, the effect was statistically non-significant; statistically higher nodulation in treatments receiving Fasal Amrit (particularly T_6 and T_7) may be attributed to improved soil moisture status and better rhizosphere aeration, which enhance rhizobial activity. Hydrogels have been reported to provide a stable microenvironment for root-microbe interactions by improving soil hydro-physical properties (18). However, root nodulation is a complex physiological process influenced mainly by soil nitrogen status, microbial population and plant genotype. Therefore, the polymer's influence may not be strong enough to produce statistically significant changes (25, 26).

Root length at flowering stage and germination

The pooled data of root length at the flowering stage and germination percentage varied from 9.67–11.94 cm and 94.50–97.00 % across the treatments (Table 1). The maximum value

Table 1. Effect of Fasal Amrit application on growth parameters of cluster bean (pooled data)

Treatments	Plant height at first picking (cm)	Plant height at last picking (cm)	No. of branches/plants	No. of root nodules at flowering stage/plant (cm)	Root length at flowering stage/plant (cm)	Germination (%)
T_1	34.97	39.87	14.17	3.34	11.14	97.00
T_2	38.47	42.53	15.70	3.14	11.94	97.00
T_3	35.30	44.60	14.97	3.14	9.87	97.00
T_4	32.87	38.50	13.97	2.80	9.67	95.84
T_5	35.97	37.27	14.94	2.97	10.07	95.84
T_6	35.99	40.69	16.71	3.63	11.21	96.00
T_7	32.23	35.37	15.97	3.50	10.24	97.00
T_8	34.57	37.63	15.84	2.80	10.17	96.00
T_9	32.23	36.34	14.50	3.00	11.34	96.17
T_{10}	30.57	35.60	13.90	2.54	9.70	94.50
SEm ±	0.72	0.96	0.30	0.10	0.26	0.26
CD ($p = 0.05$)	2.32	3.09	0.97	0.34	0.81	0.80



Fig. 1. Crop stand at 30 days after sowing (DAS).



Fig. 2. Plant growth at first picking.

of root length (11.94 cm) was recorded under T_2 , followed by T_9 (11.34 cm), T_1 (11.14 cm) and T_6 (11.21 cm), while the lowest value of root length at the flowering stage was recorded under T_4 (9.67 cm). The germination percentage data varied from 94.50 to 97.00 % among the various treatments. The maximum value of germination (97 %) was recorded under T_1 , T_2 , T_3 and T_7 , while the minimum percentage of germination was obtained in T_{10} (94.50 %). However, the numerical value differences existed among the treatments; the variation was statistically non-significant, indicating that Fasal Amrit did not exert a strong influence on root elongation up to the flowering stage and on germination percentage.

Hydrophilic polymers are known to improve moisture availability and reduce the fluctuations in soil water content, which support root growth even under moderate moisture stress (27), while seed germination is influenced by seed Fasal Amrit, temperature and soil moisture during early stages (28, 29). However, Fasal Amrit enhances soil moisture retention; their influence on root proliferation and on germination percentage is often limited because the early germination and root development process relies more on seed physiology than water buffering (28, 29). Soil conditioners as well as soil amendments improve root elongation by improving soil structure, porosity and moisture-air balance, but hydrogel amendments exhibit a negligible effect on normal germination percentage under moisture conditions (30,31).

Effect of various treatments on yield and yield-attributes of cluster bean

It was revealed from Table 2 that, among the different parameters studied, cluster bean's fresh yield and dry biomass yield were statistically significantly influenced by different treatment combinations of Fasal Amrit with RDF. The data on fresh pods of cluster beans was recorded at every picking and a total of five pickings were obtained during the crop duration. The maximum fresh pod yield of 33.58 q ha⁻¹ was observed in treatment T_5 with the application of Fasal Amrit at 20 kg ha⁻¹ + 85 % RDF, whereas treatments T_2 (i.e., the application of Fasal Amrit at 20 kg ha⁻¹ + 100 % RDF) and T_3 (i.e., the application of Fasal Amrit at 25 kg ha⁻¹ + 100 % RDF) were found to be at par and recorded fresh pod yields of 31.76 and 31.10 q ha⁻¹ respectively. The lowest fresh pod yield of 24.41 q ha⁻¹ was recorded by the treatment T_7 , i.e., the application of Fasal Amrit at 15 kg ha⁻¹ + 75 % RDF. The application of 75 % RDF significantly decreased the fresh pod yield of cluster beans. The dry biomass yield was recorded after the last picking. Among the treatment combinations, the maximum dry biomass yield of

8.92 q ha⁻¹ was recorded by the control treatment (T_{10}), whereas treatment T_5 with the application of Fasal Amrit at 20 kg + 85 % RDF (8.05 q ha⁻¹) was found to be on par with the control. The minimum dry biomass yield of 5.40 q ha⁻¹ was recorded under the treatment T_3 with the application of Fasal Amrit at 25 kg + 100 % RDF. Similar improvements in yield under hydrogel application have also been reported in other field crops where enhanced soil moisture availability improved crop productivity (32).

Table 2. Response Fasal Amrit application on yield parameters of cluster bean (pooled data)

Treatments	Fresh pod yield (q ha ⁻¹)	Dry biomass yield (q ha ⁻¹)
T_1	29.82	6.57
T_2	31.76	6.73
T_3	31.10	5.40
T_4	29.15	5.61
T_5	33.58	8.05
T_6	30.71	5.74
T_7	24.41	7.09
T_8	26.76	6.74
T_9	25.93	5.42
T_{10}	26.97	8.92
SEm ±	0.47	0.34
CD ($p = 0.05$)	1.38	1.06

Effect of various treatments of Fasal Amrit on number and irrigation intervals

The data of two consecutive years on effect of various treatment combinations on number of irrigations and irrigation intervals during the crop growth period is presented in Table 3 and Fig. 3. The data on soil moisture was recorded before each irrigation using a soil moisture indicator. Based on moisture level, irrigation was given to each treatment plot. During crop growth, i.e., from sowing to crop harvest, maximum number of irrigations (9) was observed in control treatment. The minimum irrigations (6) were provided to treatment T_5 , i.e., application of Fasal Amrit at 20 kg ha⁻¹ + 85 % RDF, followed by 07 irrigations in treatments T_1 , T_2 , T_3 , T_6 , T_7 , T_8 and T_9 . The irrigation interval between every successive irrigation was recorded. The average minimum irrigation intervals of 09 days were noted in the control treatment, whereas 10 days were recorded in treatment T_4 , i.e., application of Fasal Amrit at 15 kg ha⁻¹ + 85 % RDF. The maximum irrigation interval of 14 days was noted in treatment T_5 with the application of Fasal Amrit at 20 kg ha⁻¹ + 85 % RDF.

Hydrogels improve soil water storage capacity and reduce irrigation frequency by slowly releasing absorbed water to the root zone (22). The incorporation of hydrogel or synthetic polymers increased soil moisture retention and reduced irrigation needs by

enhancing soil water availability and reducing percolation losses and the irrigation interval under polymer-treated plants could be attributed to the high-water absorption and slow-release properties of Fasal Amrit, which effectively acts as a soil moisture reservoir (17). Superabsorbent polymers improve soil hydraulic properties and water retention characteristics, particularly in sandy soils (33, 34).

Table 3. Effect of different treatments on the no. of irrigations and days to irrigation intervals

Treatments	Irrigation interval (days)	No. of irrigations
T ₁	11	7
T ₂	11	7
T ₃	11	7
T ₄	11	8
T ₅	14	6
T ₆	11	7
T ₇	11	7
T ₈	11	7
T ₉	11	7
T ₁₀	9	9



Fig. 3. Soil moisture reading before irrigation.

Nutrient (N, P and K) content in cluster bean

Data on nutrient content in cluster beans influenced by various levels of Fasal Amrit application with a combination of different percentages of RDF and control in cluster beans are mentioned in Table 4. The data of nutrient content observed that the highest nitrogen content (15.12 %) and phosphorus content (9.03 %) were recorded under the control with 100 % RDF (T₁₀), followed by treatment T₅ with the application of Fasal Amrit at 20 kg ha⁻¹ + 85 % RDF (12.28 and 8.46 %), while the higher potassium content in cluster bean was observed in treatment T₅ (5.59 %) with the application of Fasal Amrit with 20 kg ha⁻¹ + 85 % RDF, followed by the control treatment (4.79 %). The lowest value of nitrogen content (7.61 %) and content of phosphorous (5.25 %) in cluster bean was recorded by treatment T₃ with the application of Fasal Amrit at 25 kg ha⁻¹ + 100 % RDF, whereas treatment T₆ with the application of Fasal Amrit at 25 kg ha⁻¹ + 85 % RDF recorded the lowest potassium content (3.12 %) in cluster bean.

The moderate doses of Fasal Amrit (20 kg ha⁻¹) in combination with reduced fertiliser (85 % RDF) enhance the nutrient uptake by improving soil moisture retention, reducing nutrient losses and increasing nutrients availability in the root zone. Hydrogels have been reported to enhance nutrient uptake by

reducing leaching losses and maintaining nutrients within the rhizosphere (35) and in legume crops, where hydrogel application increased nutrient uptake under moisture-limited conditions by maintaining favourable soil moisture and microbial activity (17, 35).

Table 4. Impact of Fasal Amrit application on nutrient content in cluster bean (pooled data)

Treatments	Nutrient content in cluster bean (%)		
	N	P	K
T ₁	10.62	5.34	4.06
T ₂	9.74	5.95	3.76
T ₃	7.61	5.25	3.66
T ₄	8.81	5.78	3.56
T ₅	12.28	8.46	5.59
T ₆	8.97	5.35	3.12
T ₇	10.98	7.33	3.51
T ₈	10.09	7.34	4.42
T ₉	8.55	5.71	3.41
T ₁₀	15.12	9.03	4.79
SEm ±	0.37	0.26	0.18
CD (p = 0.05)	1.10	0.72	0.50

Effect on chemical properties of soil after harvest of cluster bean

Electrical conductivity of soil

Soil EC varied significantly among treatments, ranging from 0.32–0.45 dS m⁻¹, with all values remaining within the non-saline range. The highest EC (0.45 dS m⁻¹) was recorded in T₁ and T₂ (15–20 kg ha⁻¹ Fasal Amrit + 100 % RDF), possibly due to greater fertiliser salt dissolution at higher nutrient levels. In contrast, T₅ and T₆ (20–25 kg ha⁻¹ Fasal Amrit + 85 % RDF) recorded the lowest EC (0.32 dS m⁻¹), likely reflecting improved moisture retention and moderated salt concentration under polymer application. Similar trends have been reported for hydrophilic polymers reducing salt accumulation in soil (11).

Soil pH

The data on the effect of different doses of Fasal Amrit hydrogel in combination with varying levels of chemical fertiliser on soil pH are presented in Table 5. The value of soil pH showed statistically significant but agronomical minor variations among different treatments, ranging from 7.42–7.56. The lowest data of soil pH (7.42) occurred under T₅ (20 kg ha⁻¹ Fasal Amrit + 85 % RDF), while the highest value of soil pH (7.56) was obtained under T₂ (20 kg ha⁻¹ Fasal Amrit + 100 % RDF) due to the higher fertiliser application, which increased soil alkalinity due to the cation release or nutrient. The applied hydrogel in the experiment is of organic nature, which supplies the organic carbon, enhances microbial activity due to the production of weak acids during the decomposition and improves carbon stabilisation in the soil, which ultimately affects soil pH favourably (6).

Soil organic carbon

Soil organic carbon (SOC) ranged from 0.42–0.46 %, showing marginal but statistically significant differences among treatments. The highest SOC (0.46 %) was recorded in T₉ (25 kg ha⁻¹ Fasal Amrit + 75 % RDF) and T₁₀ (100 % RDF control), whereas lower values (0.42 %) were observed in T₁, T₂, T₃ and T₅. The improvement in SOC under higher polymer application (25 kg ha⁻¹), particularly with 75 % RDF, may be attributed to enhanced soil moisture conditions that favour microbial activity and residue decomposition, thereby promoting carbon stabilisation. Similar improvements in SOC under hydrogel application have been reported under water-limited environments (36).

Table 5. Effect of Fasal Amrit application on soil properties under cluster bean

Treatment	Electrical conductivity (dS m ⁻¹)	pH	Soil organic carbon (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Mn (ppm)
T ₁	0.45	7.48	0.42	121.00	22.00	210.00	0.30	1.21	1.66	2.00
T ₂	0.45	7.56	0.42	123.50	20.50	210.00	0.28	1.25	1.57	2.02
T ₃	0.36	7.49	0.42	122.00	20.00	219.50	0.25	1.26	1.55	1.92
T ₄	0.33	7.50	0.45	122.00	19.50	220.00	0.26	1.25	1.43	2.05
T ₅	0.32	7.42	0.42	120.50	21.50	216.50	0.27	1.28	1.53	2.14
T ₆	0.32	7.49	0.45	122.50	20.00	225.00	0.26	1.36	1.55	2.13
T ₇	0.37	7.53	0.44	122.00	22.50	207.50	0.27	1.40	1.64	2.13
T ₈	0.35	7.47	0.45	123.50	20.50	215.00	0.32	1.36	1.53	2.29
T ₉	0.36	7.46	0.46	124.50	21.00	217.50	0.34	1.41	1.67	2.33
T ₁₀	0.39	7.47	0.46	121.50	22.50	212.50	0.28	1.36	1.51	2.88
SEm ±	0.01	0.02	0.01	0.50	0.31	1.92	0.01	0.02	0.017	0.028
CD (p = 0.05)	0.03	0.05	0.03	1.44	0.86	4.12	0.028	0.045	0.048	0.071

Nutrient status (macronutrient and micronutrient)

The data on soil macronutrient content, viz., nitrogen, phosphorus and potassium and micronutrients, viz., Cu, Fe, Zn and Mn, were analysed before and after harvest of the crop to see the effect of different doses of Fasal Amrit with the recommended dose of fertiliser, as shown in Table 5. In the case of nitrogen, there was a minor increase in treatment T₉ (124.50 kg ha⁻¹) with the application of Fasal Amrit at 25 kg ha⁻¹ + 75 % RDF, followed by treatments T₈ and T₂ (123.50 kg ha⁻¹). The value of phosphorus content was slightly changed among the treatments, while in the case of potassium content, there were slight increases in treatment T₆ (225.00 kg ha⁻¹) with the application of Fasal Amrit at 25 kg ha⁻¹ + 85 % RDF, followed by treatments T₄, T₉ and T₅ (216.50 kg ha⁻¹). In case of micronutrients, variations for copper (Cu), iron (Fe), zinc (Zn) and manganese (Mn) were observed due to different treatment combinations compared to the initial sample; however, a specific trend was not observed.

The application of Fasal Amrit markedly influenced the availability of both macro and micronutrients, largely through its ability to improve the soil physical conditions, moisture conservation and nutrient retention mechanisms. Nitrogen availability remained within a narrow range (120–124.5 kg ha⁻¹), with slightly enhanced levels under higher polymer doses, consistent with the ability of hydrogels to stabilise soil moisture and reduce nitrogen losses by moderating mineralisation and nitrification-denitrification fluctuations. Hydrogels improve nitrogen retention by reducing evaporative losses and enhancing soil water nutrient interactions (12). Phosphorus availability also showed modest improvement with Fasal Amrit, attributable to better diffusion under increased soil moisture, lower P fixation in alkaline soils due to organic acid release due to increasing organic matter and higher microbial mobilisation solubilisation mechanisms who reported enhanced P mobility and uptake in polymer-conditioned soils (4, 11). Potassium availability improved with increasing polymer dose, which can be attributed to enhanced cation retention through the polymer's adsorption capacity and reduced leaching under moisture-regulated conditions. Similar findings have been reported where hydrogels promoted improved cation exchange and reduced K mobility in sandy soils (13).

Micronutrient dynamics also responded positively to Fasal Amrit application. Copper availability showed a slight increase, which may be attributed to improved stabilisation of organic matter, enhanced chelation of Cu ions and increased microbial activity facilitating the release of organically bound copper in soil (37, 38). Iron availability showed a similar

improvement, attributable to increased soil moisture that facilitates Fe solubility through the creation of micro-reducing zones and chelation by organic ligands produced during polymer-microbe interactions (8). Zinc availability was enhanced under polymer treatments, these effects are in agreement with earlier findings that reported increased Zn availability with hydrogel and organic amendments (31). Manganese availability also improved marginally, reflecting the polymer's ability to maintain reduced moisture conditions, prevent oxidation of Mn²⁺ to unavailable Mn oxides and enhance microbial redox transformations. Hydrogels may enhance micronutrient availability through improved soil moisture, microbial activity and chelation processes (31).

Effect of different treatments on crop economics

The economic data of different nutrient management treatments revealed that the integration of Fasal Amrit with recommended fertiliser doses significantly enhanced crop profitability. Similar economic benefits of hydrogel application through improved water-use efficiency and yield enhancement have been reported in several crops (32, 36) (Table 6). Among all treatments, the application of Fasal Amrit at 20 kg ha⁻¹ combined with 85 % RDF (T₅) resulted in the maximum net monetary returns (₹70578) and maximum benefit:cost (B:C) ratio (1.89), demonstrating the economic advantage of reducing fertiliser input while optimising soil moisture and nutrient-use efficiency through polymer application. This suggests that moderate Fasal Amrit dosage (20 kg ha⁻¹) paired with slight fertiliser reduction (15 %) created an ideal balance between input cost and crop productivity, which is consistent with previous findings where hydrogel application improved economic returns in water-limited cropping systems (32). A comparable economic performance was recorded in treatment T₂ (20 kg ha⁻¹ Fasal Amrit + 100 % RDF), which achieved (₹61826) net returns and a B:C ratio of 1.77, statistically at par with T₅. The high profitability under these treatments may be attributed to Fasal Amrit proven ability to enhance nutrient retention, stimulate microbial activity and improve water-use efficiency, resulting in higher yield at modest additional cost, while the lowest net returns (₹31503) and B:C ratio (1.40) were observed under treatment T₇ (15 kg ha⁻¹ Fasal Amrit + 75 % RDF). Although higher polymer dosage improved soil moisture dynamics, the cost of an increased Fasal Amrit rate coupled with reduced fertiliser input likely limited yield gains, making the treatment economically less viable. These findings align with earlier studies showing that optimised doses of soil conditioners or hydrogels, when integrated with balanced fertiliser management, can enhance crop productivity and economic returns under moisture-limited environments (32, 36).

Table 6. Economics of various treatment applications under cluster bean

Treatments	Gross monetary return (₹ ha ⁻¹)	Cost of production (₹ ha ⁻¹)	Net monetary return (₹ ha ⁻¹)	Benefit: cost ratio
T ₁	132973.70	78645.90	54327.80	1.68
T ₂	141472.13	79645.90	61826.23	1.77
T ₃	137988.33	81645.90	56342.43	1.69
T ₄	129550.25	78299.30	51251.45	1.65
T ₅	149876.95	79299.30	70578.15	1.89
T ₆	136431.20	81299.30	55131.90	1.67
T ₇	109538.91	78035.80	31503.11	1.40
T ₈	119519.25	79035.80	40483.45	1.51
T ₉	115515.65	80535.80	34979.85	1.43
T ₁₀	121148.74	71108.40	50040.34	1.69

Conclusion

Application of Fasal Amrit at 20 kg ha⁻¹ combined with 85 % RDF resulted in the highest fresh pod yield of cluster bean, followed by 20 kg ha⁻¹ Fasal Amrit with 100 % RDF and 25 kg ha⁻¹ Fasal Amrit with 100 % RDF. The longest irrigation interval, accompanied by reduced irrigation was recorded under the application of Fasal Amrit at 25 kg ha⁻¹ combined with 100 % RDF.

Findings from the two-year study demonstrate that integrating Fasal Amrit with optimised fertiliser doses enhances cluster bean productivity through improved soil moisture regulation, nutrient retention and rhizosphere functioning. Early growth traits such as branching, nodulation, root length and germination remained statistically unchanged. However, Fasal Amrit significantly improved plant height, fresh pod yield, irrigation efficiency and nutrient uptake, with the combination of 20 kg ha⁻¹ Fasal Amrit and 85 % RDF emerging as the most effective and economically viable treatment. This nutrient-saving combination not only produced yields comparable to or greater than those achieved with full RDF but also reduced irrigation requirements and improved soil chemical properties without inducing salinity or undesirable pH shifts. The results collectively indicate that moderate Fasal Amrit application offers a sustainable strategy for improving the water-use efficiency, stabilising nutrient dynamics and improving profit margins in cluster bean cultivation, particularly in moisture-constrained production environments.

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Authors' contributions

RP initiated and coordinated the trial in collaboration with BAIF on behalf of EF Polymer Pvt. Ltd. and supervised the overall implementation of the research activities. GAS contributed to the manuscript drafting, editing and interpretation of the results. NLG is the developer and patent holder of the technology used in this study and provided the technological foundation for the research. MAK assisted in manuscript drafting and supported data analysis. AKB and ST contributed to data analysis and interpretation of the experimental results. All authors read and approved the final manuscript.

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During the preparation of this work, the authors used QuillBot to make minor grammatical corrections. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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